1934

A new theory of the spalling of fireclay products with relation to thermal expansion

Robert LeGrande Stone

A NEW THEORY OF THE SPALLING OF FIRECLAY PRODUCTS WITH RELATION TO THERMAL EXPANSION.

BY

ROBERT LEGRANDE STONE.

- - -

A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

BACHELOR OF SCIENCE IN CERAMIC ENGINEERING

Rolla, Mo.

1934.

Approved by ________________________________

Acting Head of the Department of Ceramics.

ACKNOWLEDGMENTS.

The writer wishes to express gratitude to Professor Dodd for his helpful suggestions in the running of the thesis and building of the furnace. The following organizations aided in supplying the material for the furnace and tools with which to work:

The United States Bureau of Mines,
The Mechanical Engineering Department,
The Metallurgy Department,
The Physics Department, and
The Ceramics Department.

TABLE OF CONTENTS.

LIST OF ILLUSTRATIONS.

LIST OF GRAPHS.

A NEW THEORY OF SPALLING AND FURNACE FAILURES.

INTRODUCTION.

There is one factor that is responsible for much of the failure of refractories in furnaces and other metallurgical processes and boilers, namely spalling. Many times this action has been the cause of roofs to cave in, side walls to slump, and bungs to fail. Consequently it is a factor that is of utmost importance. The erosion and slag effects are also of greatest importance to refractory stability.

Spalling, as referred to refractories, is defined[1] as the breaking or crushing of the unit due to thermal, mechanical, or structural stresses, presenting newly exposed surfaces of the residual mass.

Taking the above definition for what it is worth and studying the various parts of it in detail, some light may be thrown on the subject of spalling, its cause and cure. First of all, it is failure of the refractory due to stresses - mechanical, thermal, or structural - which

---

[1]Standard Definition of Spalling, Amer.Soc. for Test. Mater.Designation: C 71 - 31.

exposes new surfaces to the action to which the refractories are subjected. Particularly is it important to note that the failure is due to stresses of any of the forms mentioned.

F.H.Norton[1] in his textbook on refractories, outlines a theory of spalling that has met much criticism by F.W.Preston[2]. Mr.Norton contends that the spalling action is due to:

1. A temperature gradient in the brick due to uneven heating or cooling, which is sufficient to set up stresses of such magnitude as to cause the failures.

2. Compression in the structure of refractories, due to expansion of the whole from a rise of temperature, sufficient to cause shear failures.

3. Variation in coefficient of expansion between the surface layer and the body of the brick, due to surface slag penetration or to a structural change, great enough to shear off the surface layer.

Even though the stresses and strains in solid

---

[1]Norton, F.H., Refractories, pp.339-368, McGraw-Hill Book Co., 1931.

[2]Preston, F.W., A.Theory of Spalling, pp.131-133, Jour.Amer.Cer.Soc., Vol.16, No.3, 1933.

materials is not very well understood, much light has been thrown on the subject by Booze and Phelps[1], Greene[2], and Preston[3].

In a Thesis by Beinlich there are shown many pictures of actual spalled brick obtained by the standard water dip spall test[4]. Mr.Norton also gives diagrams of the same nature as the pictures shown by Mr.Beinlich. The brick take the shape shown below when spalled:

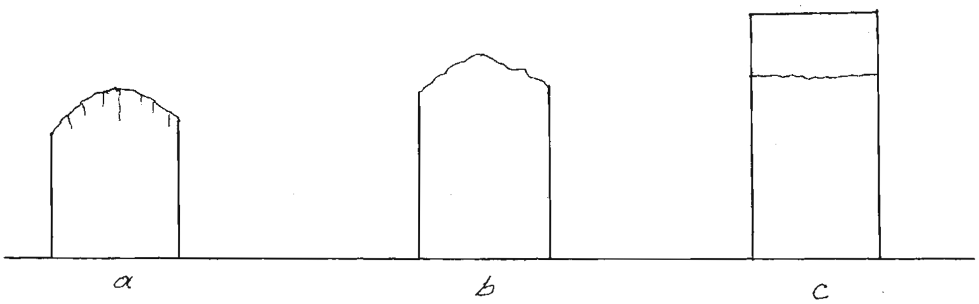


Fig.1.

The spalling as shown in Fig.1, a and b, is due, in our opinion, to the disintegration of the bond by chilling or rapid heating which allows the action of c to take

1Booze, M.C., A Study of Spalling Tests for Fire Clay Brick, Proc.Amer.Soc.Testing Materials, Vol.26,1, pp.43-57, 1926.

2Greene, A.T., The Spalling of Refractory Materials, Trans.Eng.Cer.Soc.,Vol.25, pp.428-470, 1925-1926.

3Preston, F.W., The Spalling of Bricks; Jour.Amer.Cer. Soc., Vol.9, 10, pp.654-658, 1926.

4Present Amer.Soc.Testing Materials Tentative Standard, Serial Designation: C 38 - 31 T.

place. Consequently the form taken by Fig.1 is of the most importance.

The most commonly employed spall test today is the water dip test where the brick ends are heated to 1350°C. for one hour, plunged into cold water to a depth of 2 inches for 3 minutes and then allowed to steam for 5 minutes[1]. The object of spall tests is to simulate the action of actual service in the laboratory, and in a comparatively short time obtain results indicative of the life of the brick. Mellon Institute has devised a method of testing by an air blast which seems to simulate service conditions better than the water dip test and is now adopted by the Amer.Soc. for Testing Materials.

Any of these tests givethe condition of condition (1) as given by Mr.Norton - that of a thermal gradient in the brick sufficient to cause the end of the brick to shear.

PURPOSE AND THEORY OF THIS EXPERIMENT.

The purpose of this thesis was to find some means of coordinating the thermal expansion with the spalling life of refractories. The expansion curves were obtained

[1]Present Amer.Soc.Testing Materials Tentative Standard: Serial Designation: C 38 - 31 T.

by heating and cooling in the furnace described later.

The heating rate adopted is as follows:

Time		Temperature
Hours	Minutes	°C.
0	0	Room
0	15	200
0	30	400
0	45	600
1	00	800
1	15	1000
1	30	1100
1	45	1200
2	00	1300
2	7-1/2	1350

The brick were then cooled along the reverse of the curve.

Considerable modification of the heating and cooling schedule was necessary due to the fact that the brick begin to contract near 1000°C. This necessitates that the temperature be maintained at that temperature for a definite longer period of time. Each time that the brick specimen began to shrink, the temperature was held constant at the next interval for 30 minutes and the reading taken as constant. In most cases, the contraction had stopped; however, this schedule was adopted whether the contraction had ceased or not so that there would be uniformity of data.

THEORY.

It is very evident that there will be stresses set up in the interior of any substance that is not of constand temperature throughout; that is, there will be stresses when there is a temperature gradient from the one surface to the other, or from the surface to the interior. These stresses are set up by virtue of the thermal expansion of the material not being a straight line.

Following is a sketch which will be used:

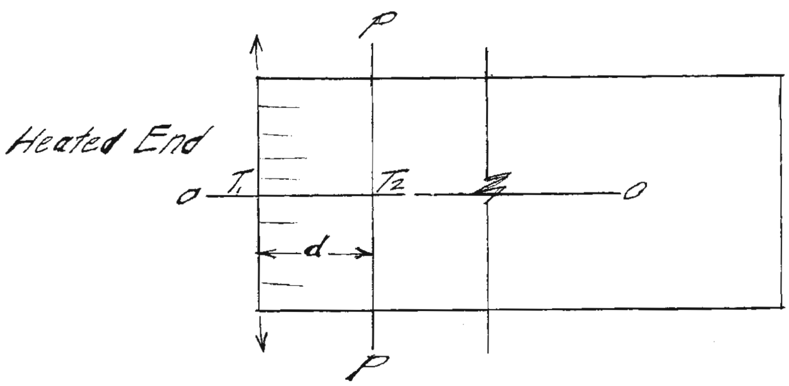


Fig.2

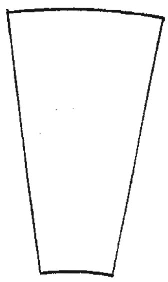


Fig. 3

If the coefficient of thermal expansion were a constant (and it isn't truly in any solid) with each degree of temperature rise up to the critical temperature of the substance the body would assume the shape given in Fig. 3. That is the body would assume a fan shape and establish a point of equilibrium.

There are two other considerations:

1. That the temperature gradient is not uniform throughout the mass, in which case, there would be the tendency for the mass to assume the shape shown in Fig. 4:

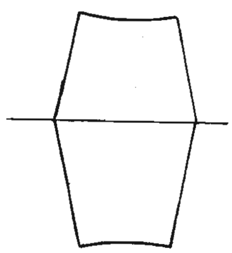


Fig. 4

Conclusion from this condition: the mass would have to be perfectly elastic to withstand the bending action and no refractory has such a physical property. It is true that refractory material has the property of bending around the grog particles which is slightly analogous to elasticity and is given by the modulus of elasticity. Mr.Norton takes this factor into consideration in compounding his spalling formula.

2. The second consideration is that of the variable coefficient of expansion of practically all substances. As will be shown later, this is a crucial point in the consideration of this thesis. If a mass were subjected to heat at one end, as in a refractory brick, there would be the tendency present for portions of the brick to rotate about other portions. This is exemplified in Fig. 2 where the temperature gradient is constant and the mass would, if the coefficient of expansion were constant, assume the form of Fig.3. When such a condition exists, the portion of the brick (the bond) that holds the particles together, will be under direct tensile stress. The bond has the tendency to disintegrate, as will glass when chilled, thus leaving the action of the thermal expansion to separate the grog particles and the fireclay from the bond.

Taking this same consideration from another point of view, supposing that the coefficient of expansion suddenly changed at some critical temperature while the mass is still perfectly solid as a whole, then there would be a reversal of the stresses while the brick were at the high temperature. Fig. 5 shows how this would act:

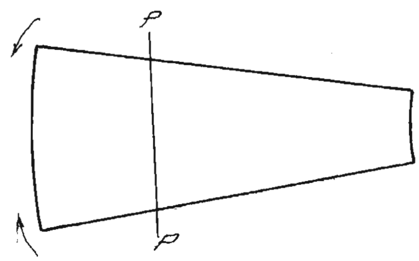


Fig. 5

P-P is the plane through the brick where the temperature is just at the critical point. Above this plane the coefficient of expansion has dropped and there is a tendency for the surface to contract.

The particles do not move too freely and there is a tendency for tensile stresses to be set up and tear the surface apart.

In this thesis the author has endeavored to measure this difference of thermal expansion that it might throw some light upon spalling.

APPARATUS.

The apparatus employed is a modification of that used by the Bureau of Standards[1]. Figures 1 to 4 inclusive give the layout of the furnace. The mirror attachment is made from an old clock cut away so that only the main spring wheel and the wheel adjoining it are used. The mirror is mounted on a piece of bakelite with Soldine cement.

The specimen is mounted on a length of three-eighths

---

[1]Thermal Expansion of Chrome and Other Refractories: United States Bureau of Standards, Vol.June, 1930.

inch fused quartz rod, being held vertically with rings of asbestos until the upper fused quartz rod is in place. The asbestos fuses away and leaves the specimen free to move at the higher temperatures.

The upper quartz rod extends up through the insulating material. On top of this rod is mounted a brass knife edge on which rests the pinion of the clock as shown in Fig. 4. The expansion of the specimen is transmitted by this rod to the clock which turns the mirror. The deflection caused by the expansion is read on the 50 cm. scale mounted on the rack 65 cm. from the pinion of the mirror wheel. These dimensions were held constant throughout the experiment.

The specimen is protected from any flame impingement by an alundum muffle. Into the side of this muffle is mounted another alundum tube so that the true temperature inside the muffle can be obtained. All joints are cemented with high temperature cement.

The temperature was measured by a Nobel metal thermocouple up to 780°C. and from that temperature on both the thermocouple and the disappearing filament optical pyrometer were used. The temperatures as obtained with the two instruments agreed within 5 degrees throughout the range up to 1350°C.

The mirror was adjusted to zero by means of the adjustment screw at the bottom of the lower quartz rod.

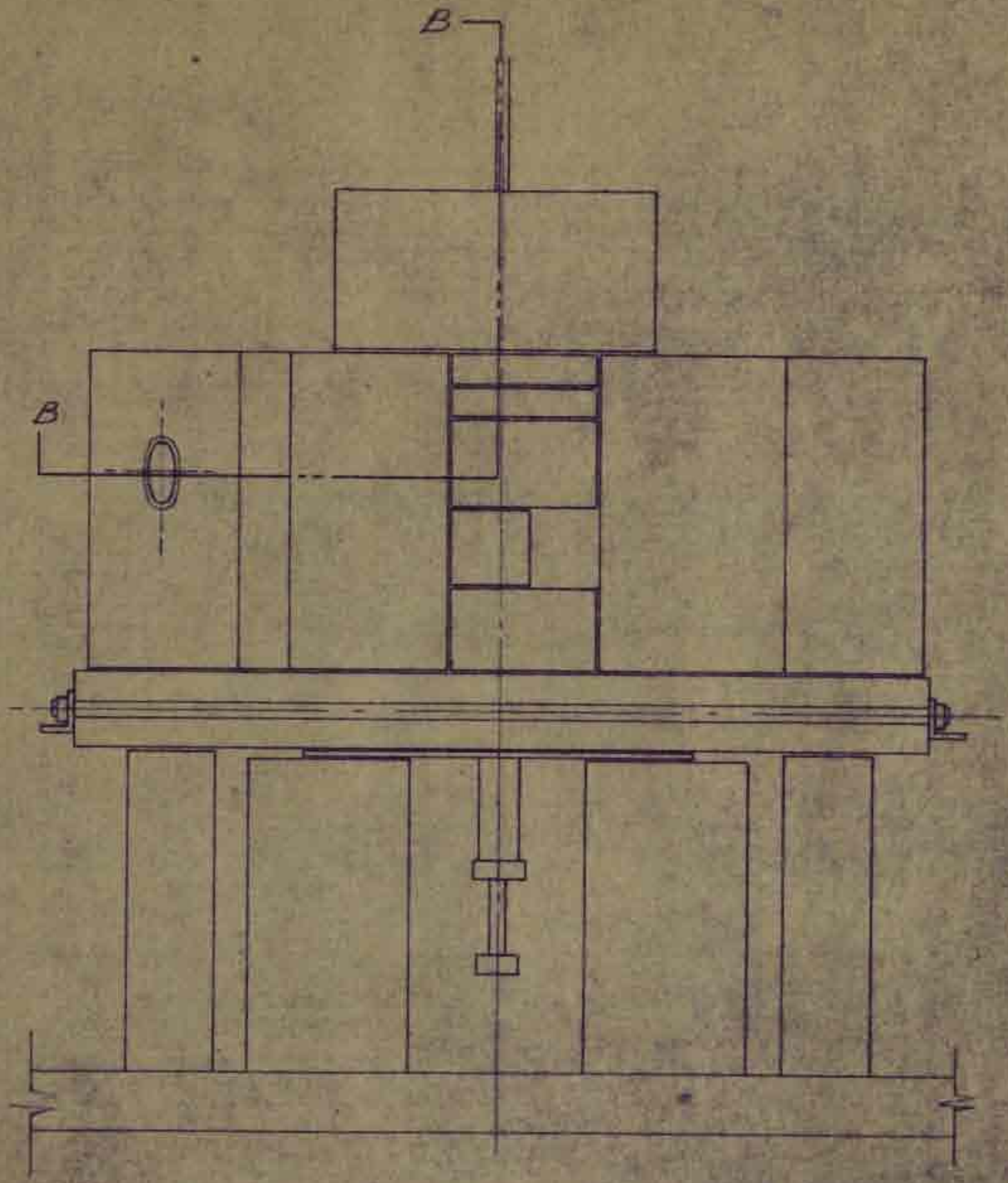
Skell gas was used as the fuel.

CALIBRATION OF THE FURNACE.

In order to get the true expansion of the specimen alone without any of the furnace expansion it was necessary to calibrate the furnace against some known material. For this purpose, a rod of Stainless "I" steel was selected which has a very nearly constant expansion coefficient between 70°F. and 1500°F.

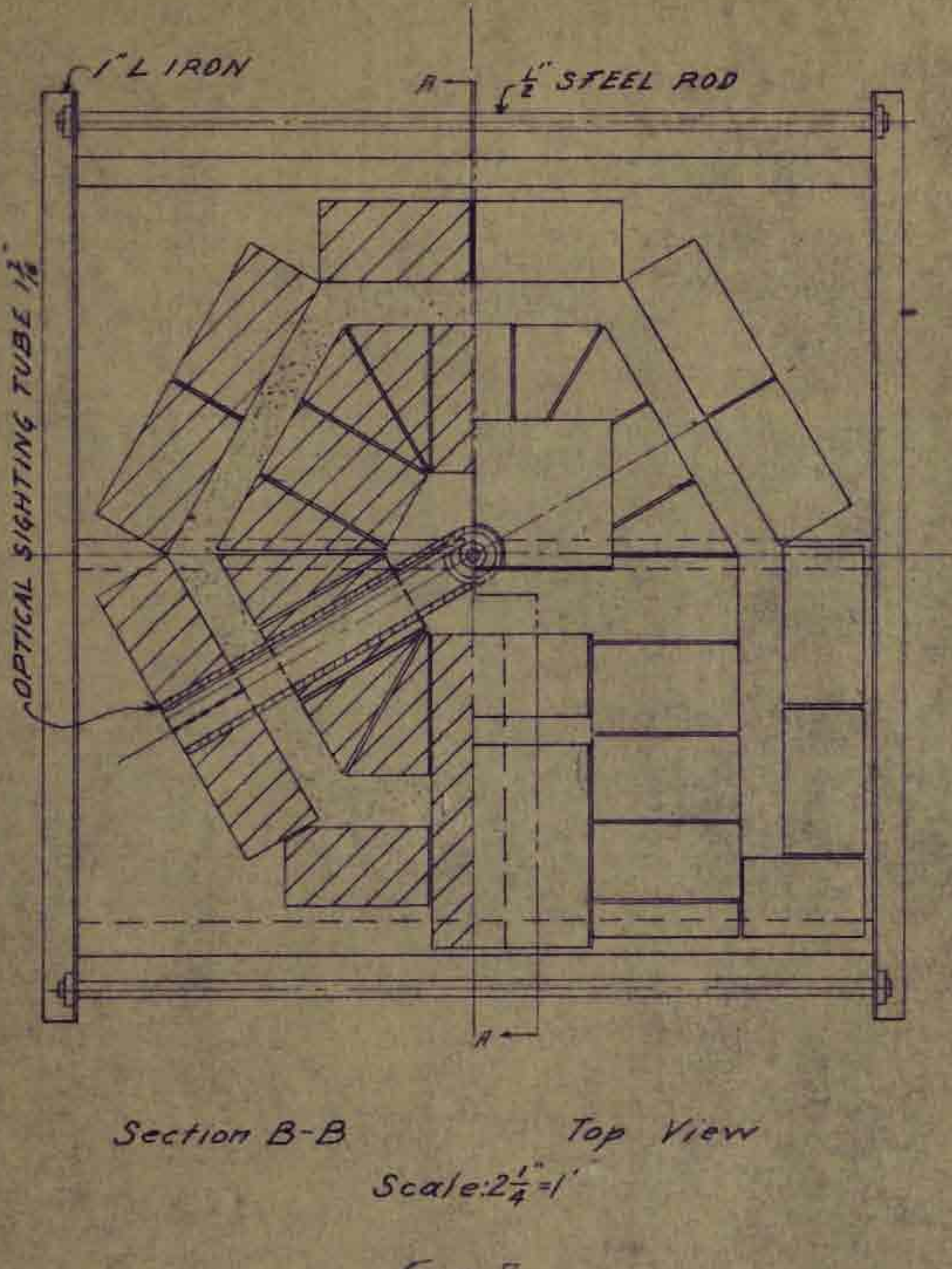
The expansion was sufficient to bring the mirror readings off the scale, so the adjustment screw was turned enough to bring the reading back to the lower end of the scale. This had to be done in all of the runs, record being kept of the change. To get the true readings, it was necessary to convert the vertical scale readings to that of a circular scale having a radius equal to 65 cm. Fig. 1 shows the method employed to convert the divisions.

Further calibration was used to find the movement of the specimen in terms of the circular scale divisions. This was done by means of an Ames Dial. The movement, actual, was measured with the dial, and the divisions equal to the movement recorded. This gave



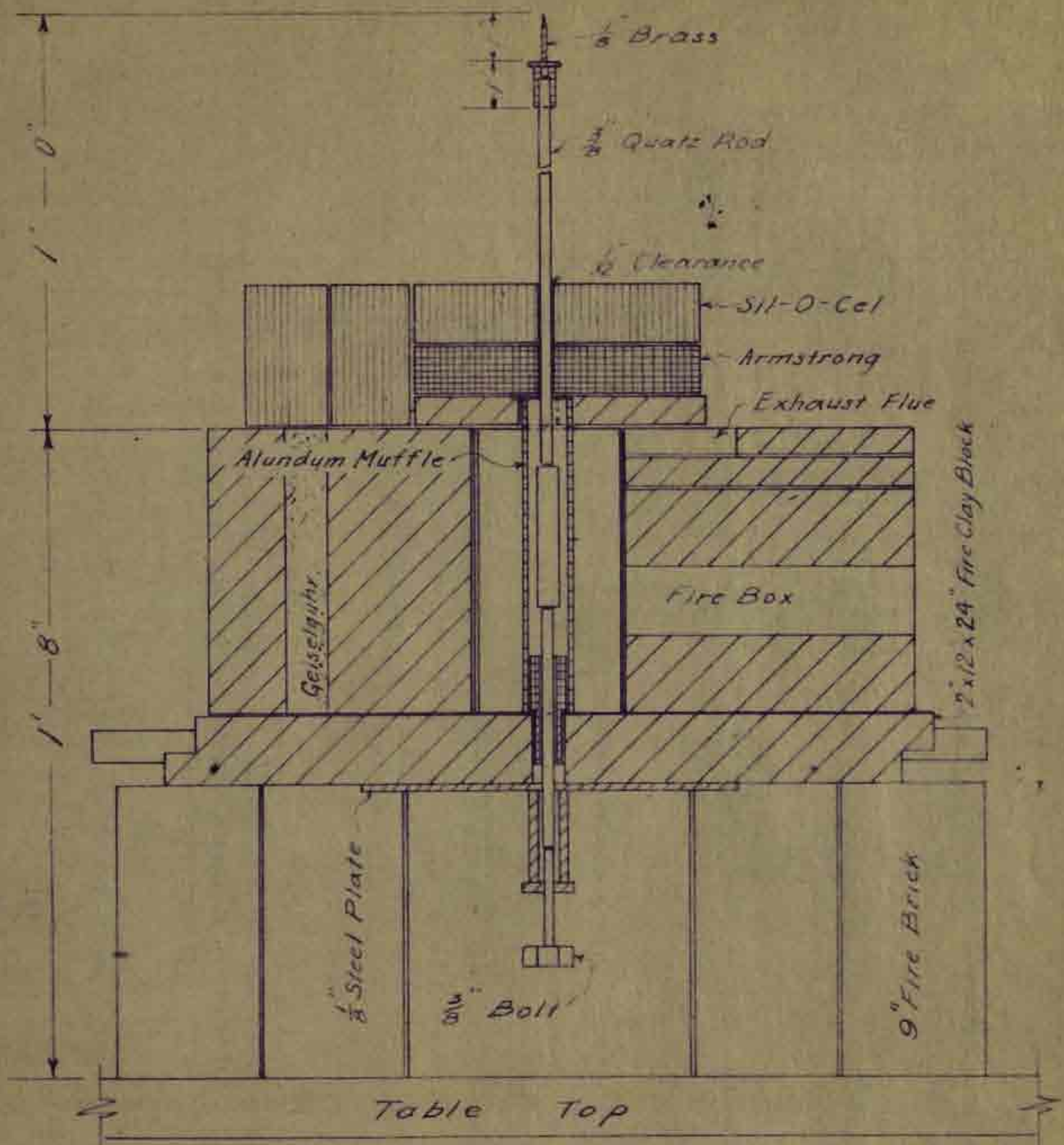
Front Elevation
Scale: $2\frac{1}{4}'' = 1'$

Fig. 6



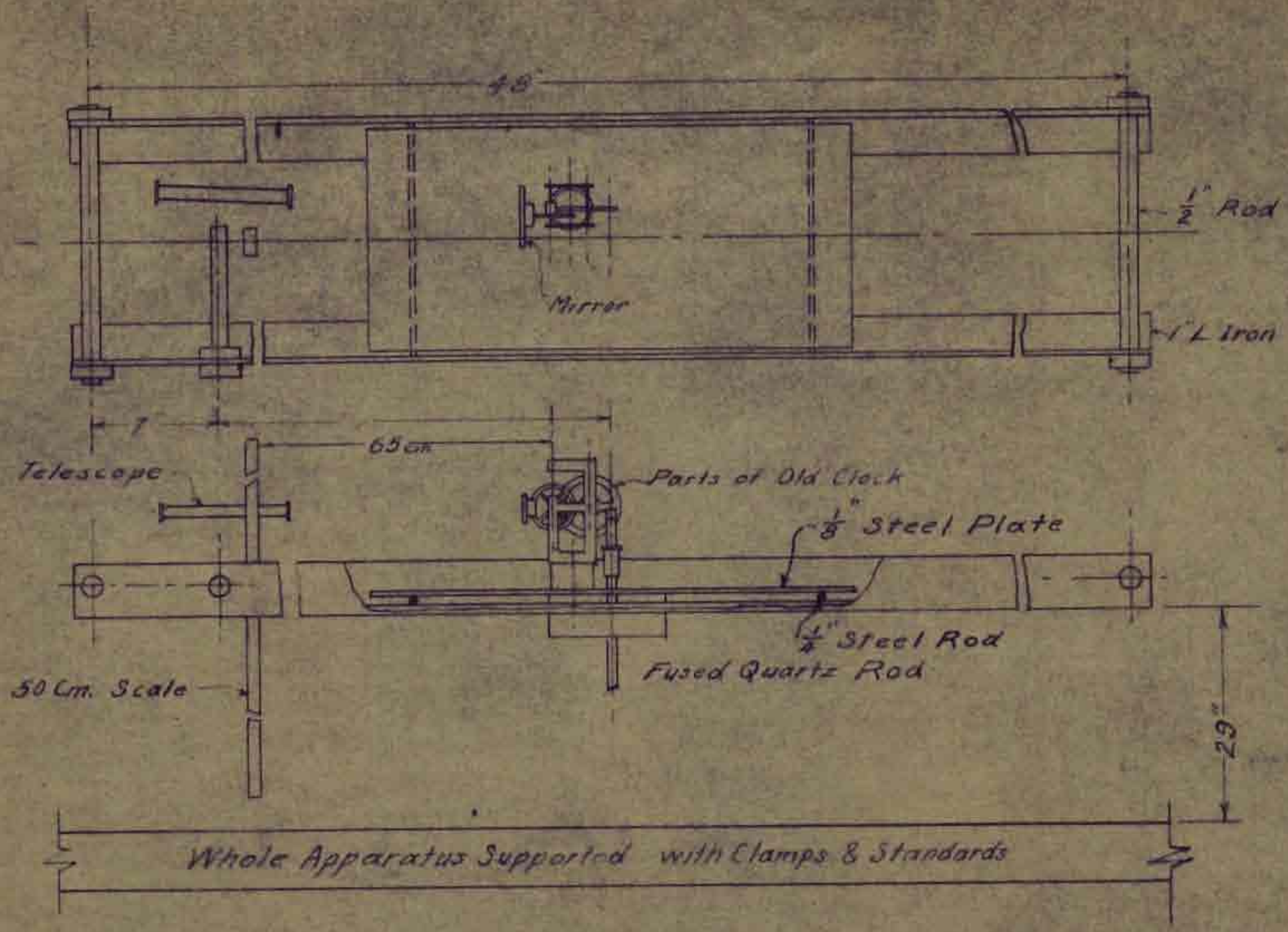
Section B-B Top View
Scale: $2\frac{1}{4}$" = 1'

Fig. 7



Section A-A
Scale. $2\frac{1}{4}"=1'$

Fig. 8



Detail of Mirror & Telescope System
Scale: 3" = 1'

Fig. 9

RELATION OF VERTICAL & CIRCULAR SCALES

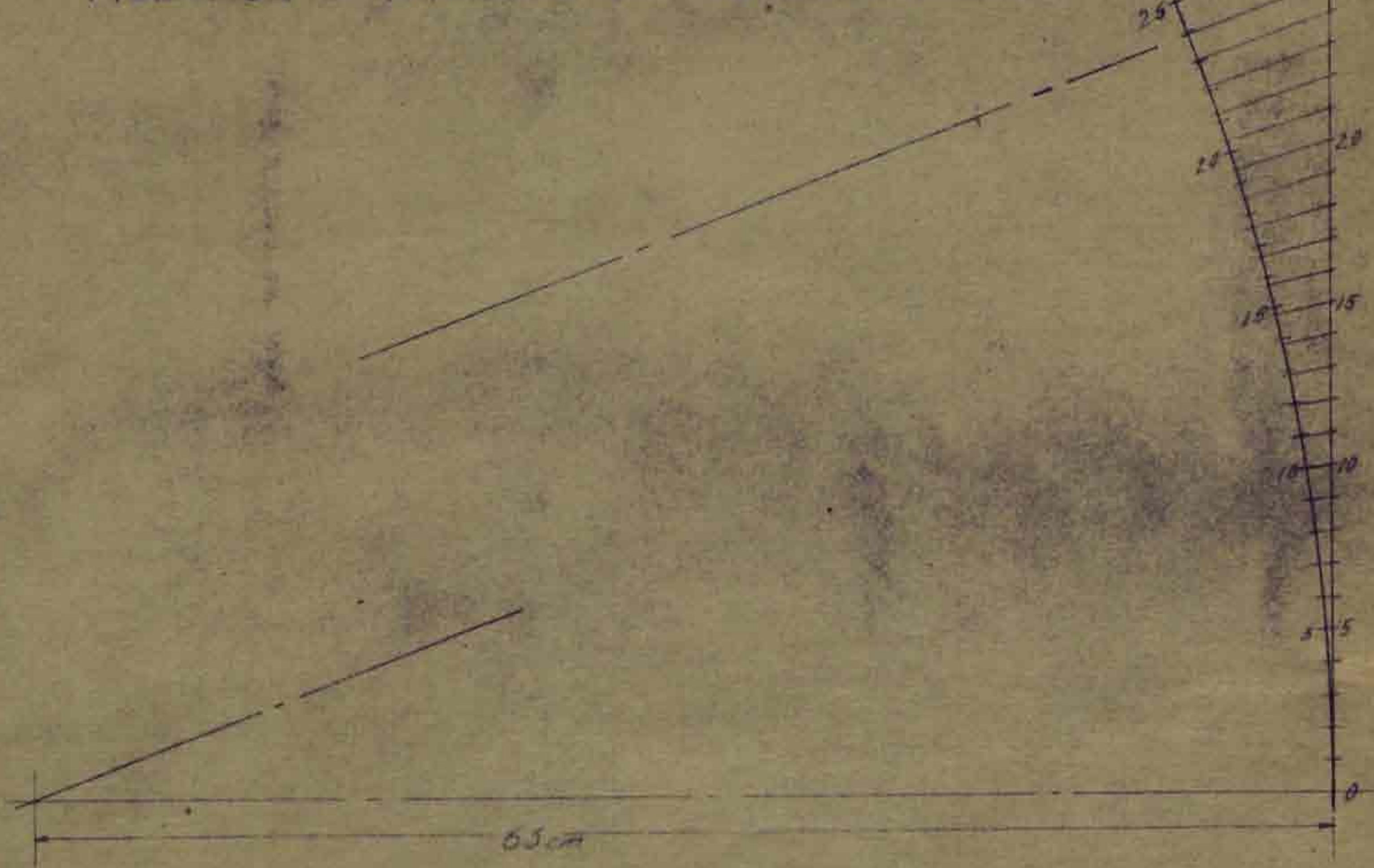
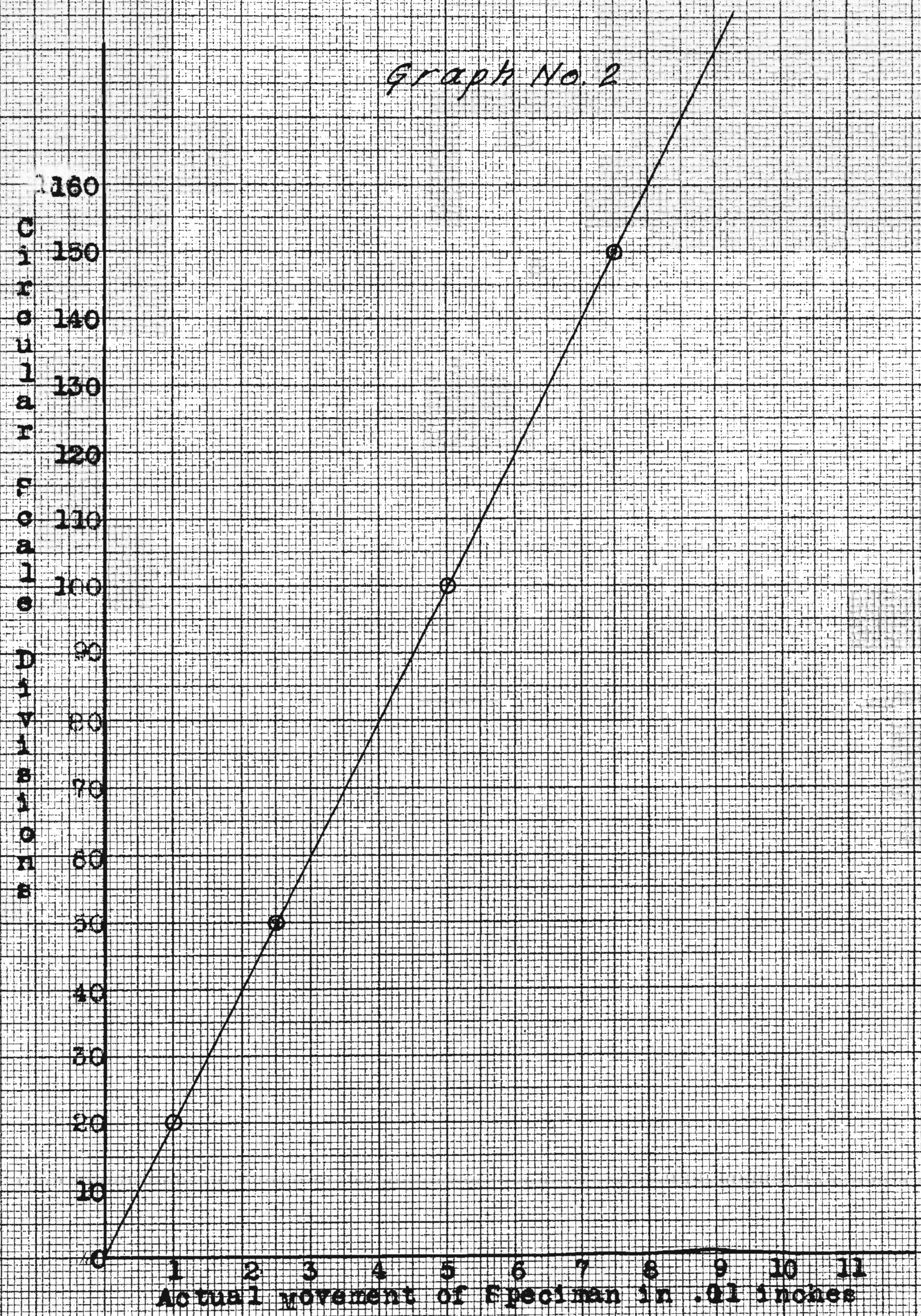


Fig. 10

Graph No. 1

Graphical Relation of Vertical Scale to Circular Scale Divisions



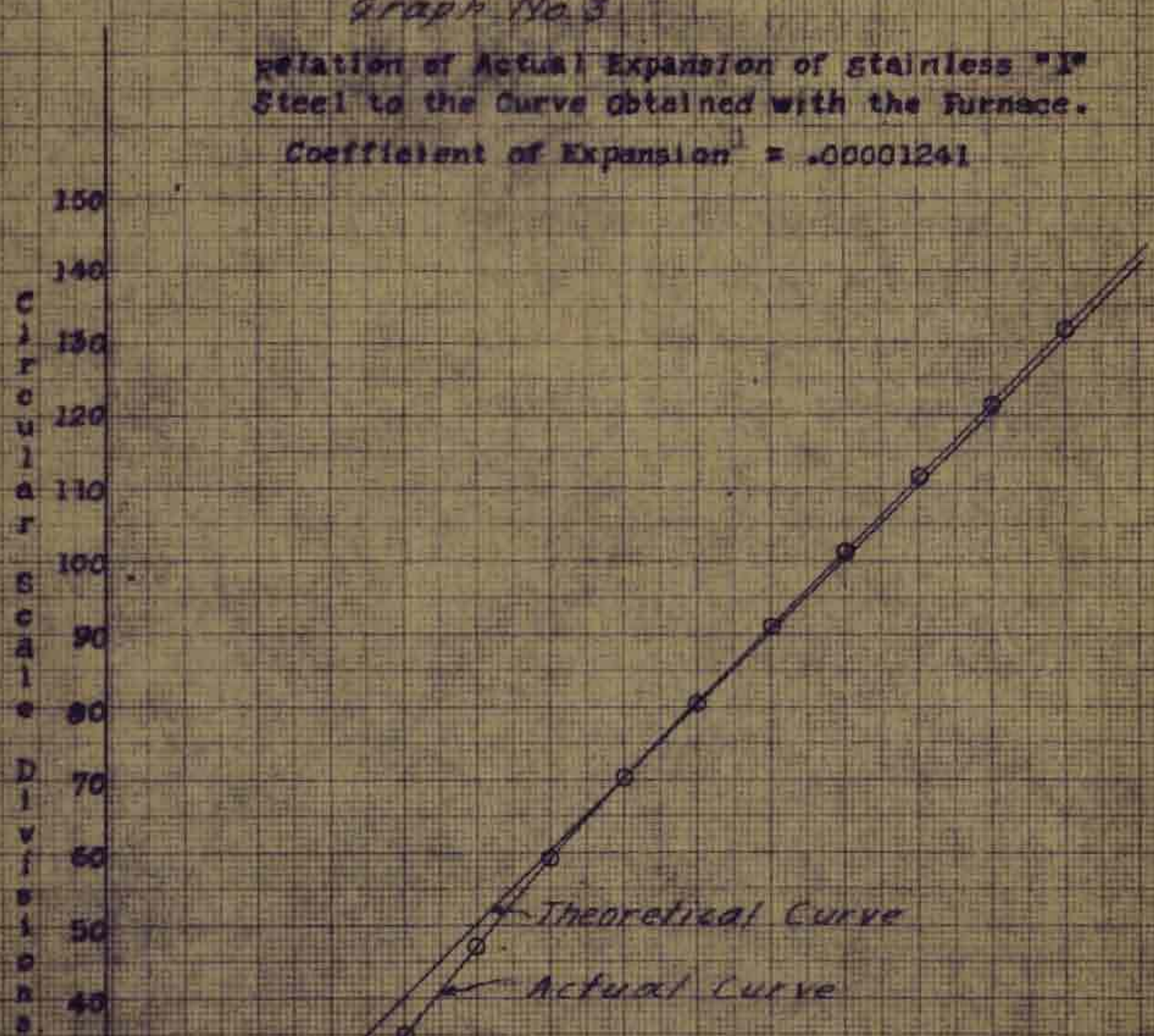
Relation of Actual Movement as Delivered by the Quartz Rod to Scale Divisions

EXPANSION DATA

on

STAINLESS "I".

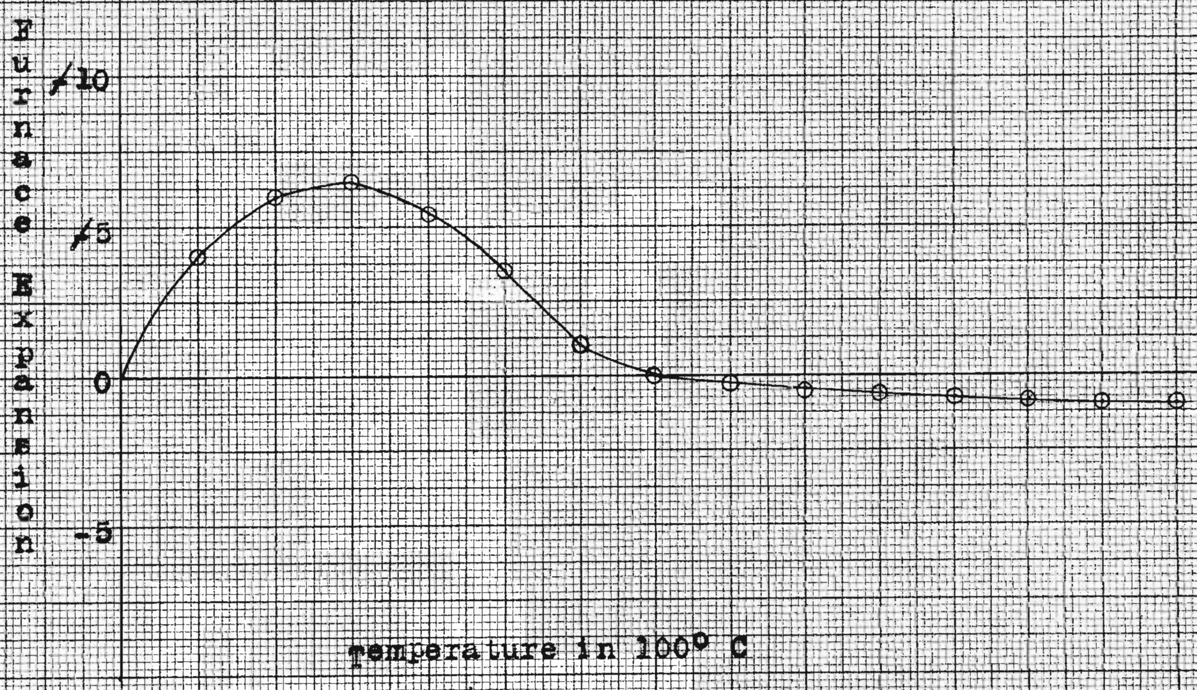
Temp.	Scale
0	0
100	5.3
200	13.0
300	23.0
400	35.0
500	47.0
600	59.0
700	70.1
800	80.2
900	90.4
1000	100.4
1100	110.3
1200	120.3
1300	130.3


Graph No 3
Relation of Actual Expansion of Stainless "I" Steel to the Curve Obtained with the Furnace.
Coefficient of Expansion = .00001241
Circular Scale Divisions
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Theoretical Curve
Actual Curve
1 2 3 4 5 6 7 8 9 10 11 12 13
Temperature in 100° C.

Graph No.4

Expansion of the Furnace

Note: To get the actaal expansion curve of the material, add or subtract the values from the following curve to the values actually obtained at the temperature with notice to the sign given below.



the calibration of the furnace as .0005 inches movement of the specimen per one cm. division of the circular scale. From Graphs 1 and 2 are obtained the expansion and circular divisions for the steel employed. These values were plotted on the graph with the actual expansion curve of the steel. From this the expansion of the furnace was obtained and plotted on Graph 4. The values of the furnace movement were added or subtracted to the curves obtained for the specimen of brick to give the true expansion curve of the brick.

MAKING OF SPECIMEN OF BRICK.

The following makes of brick were used.

BRAND	SPECIMEN.
1. A.P.Green Empire (Dry Press)	
2. Evans and Howard	
3. Queen's Run	
4. Laclede King	
5. Wellsville HIHEAT	

The specimen selected in each case was a transverse section of the brick taken as near the center of the brick as possible. The brick was chipped with a chisel down to approximately 1" square and then ground down on an emery wheel to 3/4" diameter.

After obtaining the specimen of the correct diameter, it was then ground and polished on the ends to exactly

4.4" in length. All specimens including the steel rod were made this length to prevent further calculations of results.

METHOD OF PROCEDURE.

The prepared specimen was mounted in the furnace as previously given and the mirror adjusted to the zero mark. The furnace was then heated according to the schedule outlined, care being taken to note the temperature at which the specimen began to contract. In most cases this point was very definitely marked by a rather sharp drop in the scale. After the furnace had attained the maximum temperature of 1350°C. the flame was shut off and the furnace allowed to cool slowly. The readings of the scale were taken in the same manner as upon heating.

The specimen was not moved or touched after the first heat. When the furnace had reached room temperature, the zero mark was noted, and the same schedule followed in heating the specimen again.

The second set of data was plotted with the new zero mark as the end point of the first run.

PRESENTATION OF DATA.

In the following columns are given the data as collected and the calculated data. The corrections to be applied are obtained from Graph 4 and are either added or subtracted as indicated from the graph.

The per cent expansion = $\frac{\text{expansion}}{\text{Original length}} \times 100$

This gives the per cent expansion at any temperature with relation to the original length. The expansion being found from Graph 2 in terms of the circular scale readings. The expansion is expressed on the curves in .1%. One division of the scale represents .11% expansion, and this can be read directly from the graphs after plotting.

The coefficient of expansion is defined as the expansion per degree temperature rise, in our case in terms of degrees centigrade.

$$\text{Coef. of Expan.} = \frac{\%\ \text{Expan.} \times .01}{\text{Temperature in }^\circ\text{C.}}$$

The values thus found are plotted against temperature as in the case of per cent expansion.

TABLE I.

First Run on Specimen No.1

Temp.	Uncorrected Scale		Corrected Scale		% Expansion	
	Up	Down	Up	Down	Up	Down
0	0	36.3	0	36.3		
100	4.0	35.0	9.0	35.0	.104	-.396
200	11.5	34.0	17.5	34.0	.193	-.385
300	19.5	32.8	26.0	32.8	.276	-.361
400	27.0	31.5	32.0	31.5	.352	-.346
500	34.3	30.0	38.5	30.0	.423	-.332
600	41.2	29.0	44.3	29.0	.489	-.319
700	48.5	28.0	50.2	28.0	.555	-.308
800	55.0	26.8	56.0	26.8	.616	-.296
900	61.3	24.7	61.3	-24.7	.676	-.275
1000	65.7	-21.5	65.7	-21.5	.720	-.239
1056	67.3		67.3		.743	-.213
1100	49.0	-18.0	49.0	-18.0	.539	-.198
1200	31.0	-19.0	31.0	-19.0	.341	-.209
1300	+4.0	-20.8	+4.0	-20.8	.044	-.230
1350	-21.0	21.0	-21.0	-21.0	-.231	-.231

TABLE I (Cont.)

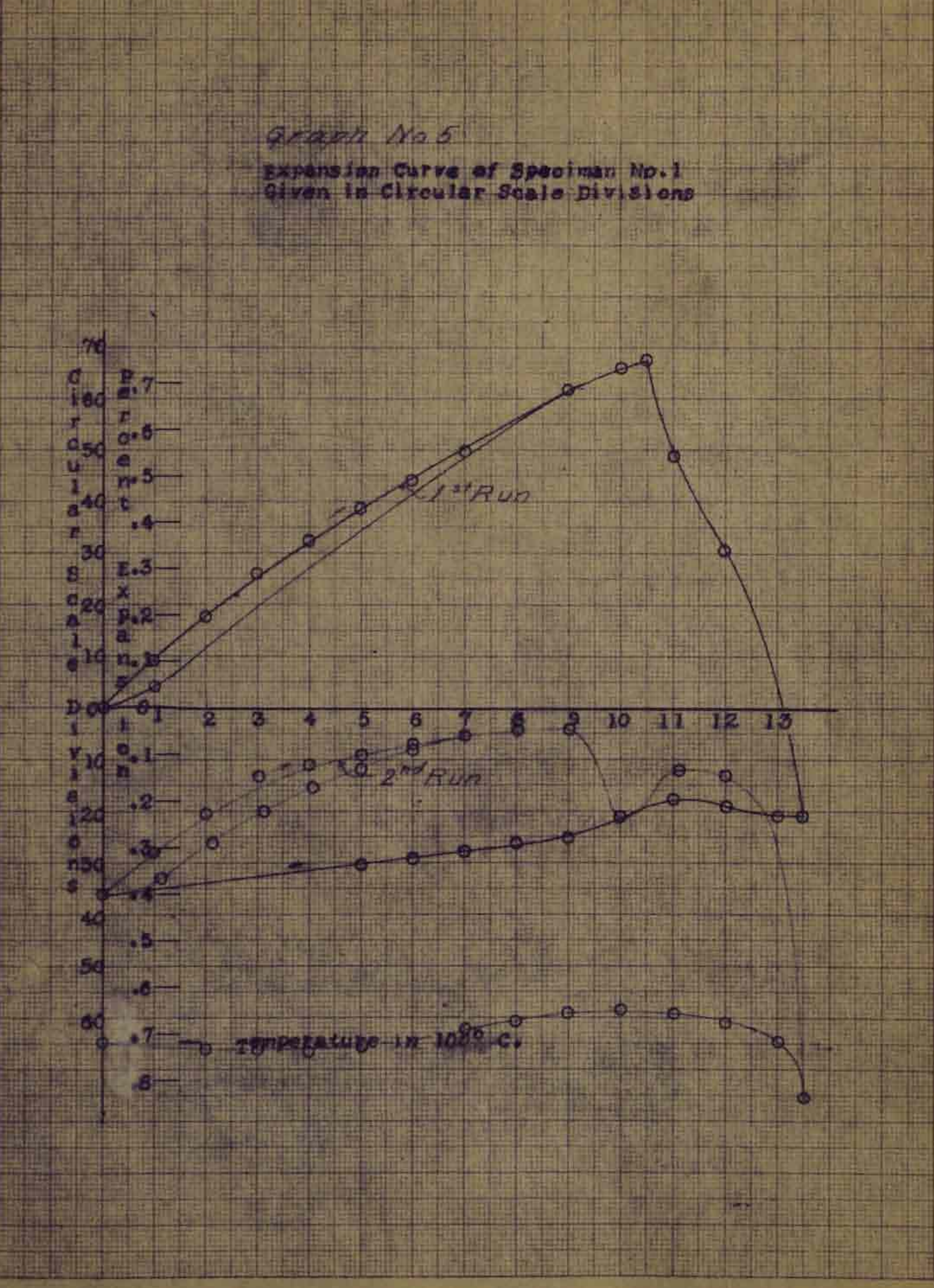
Second Run on Specimen No.1

Temp.	Uncorrected Scale		Corrected Scale		% Expansion	
	Up	Down	Up	Down	Up	Down
34	-37.3	65.1	33.3	65.1		
118	33.3	65.8	27.0	65.8	.100	-.322
212	26.4	66.0	20.1	66.0	.173	.328
315	20.1	66.4	15.1	66.4	.232	.329
403	15.4	66.6	11.6	66.6	.266	.328
500	12.3	65.0	9.1	65.0	.299	.322
600	8.0	63.9	7.1	63.9	.316	.306
700	5.6	62.8	5.7	62.8	.332	.289
800	4.8	60.1	4.8	60.1	.349	.268
900	4.5	58.8	4.5	58.8	.354	.252
1000	20.5	58.8	20.5	58.8	.167	.251
1110	12.3	59.4	12.3	59.4	.261	.253
1200	13.1	61.2	13.1	61.2	.250	.267
1300		64.3	27.0	64.2	+.107	.311
1350	74.2	74.2	74.2	74.2	-.427	-.427

TABLE I (Cont.)

Calculated Data

Temp.	Coef. of Exp. x 10^{+5}			
	1st Run		2nd Run	
	Up	Down	Up	Down
100	1.042	-3.960	.902	-3.220
200	.962	-1.975	.835	-1.690
300	.920	-1.203	.760	-1.097
400	.880	-.865	.665	-.820
500	.850	-.664	.598	-.644
600	.815	-.530	.527	-.510
700	.793	-.440	.474	-.413
800	.770	-.370	.436	-.335
900	.751	-.306	.393	-.280
1000	.720	-.239	.167	-.251
1050	.708	-.220	.186	-.239
1100	.490	-.180	.237	-.230
1200	.284	-.174	.208	-.222
1300	.034	-.177	.0823	-.239
1350	-.171	-.171	-.316	-.316


Graph No 5
Expansion Curve of Specimen No.1
Given in Circular Scale Divisions
Circular Scale Divisions
Per cent Expansion
1st Run
2nd Run
Temperature in 100° C.

Graph No.6
Coefficient of Expansion Curves for
Specimen No.1

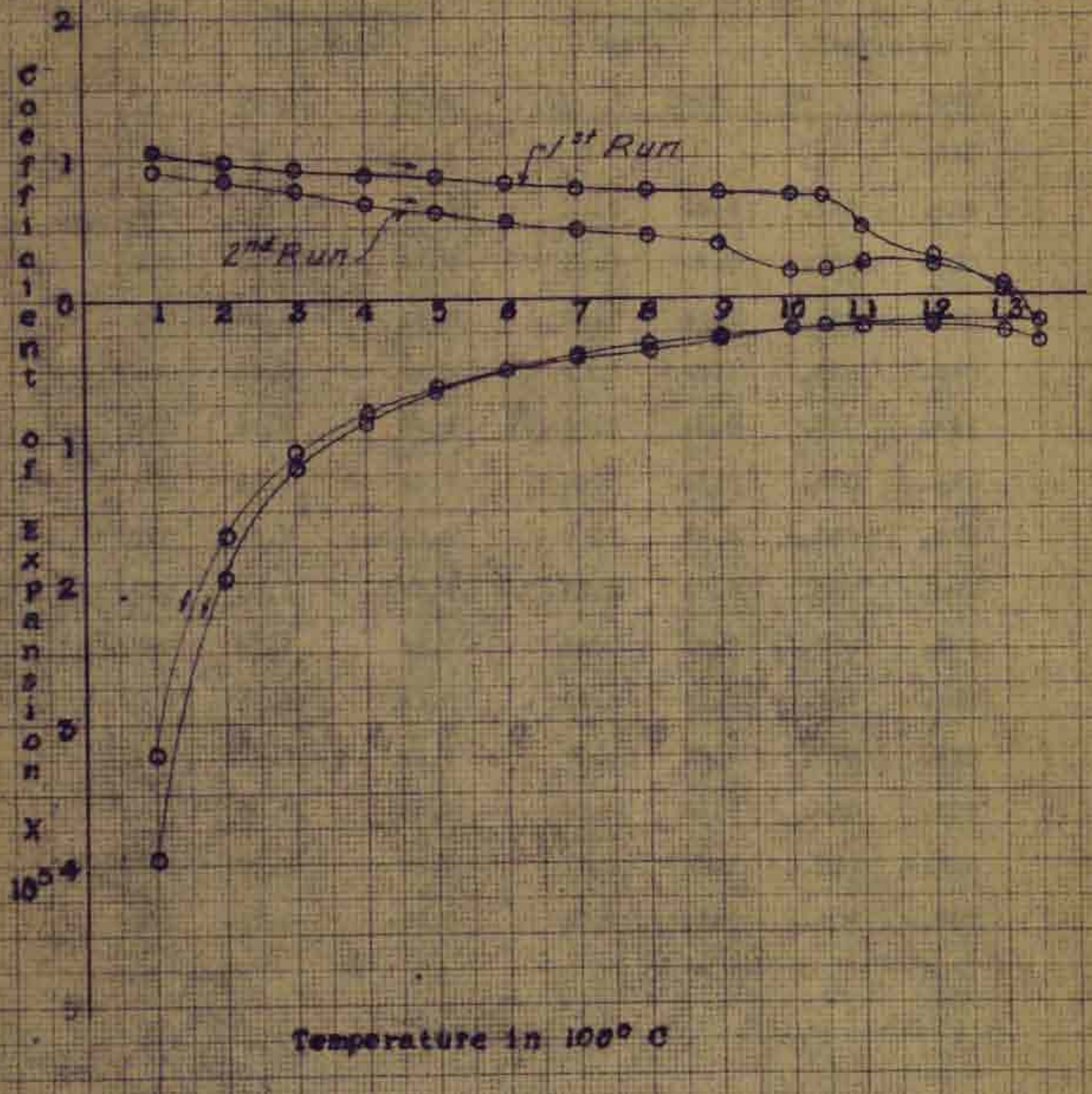


TABLE II.

First Run on Specimen No.2.

Temp.	Uncorrected Scale		Corrected Scale		% Expansion	
	Up	Down	Up	Down	Up	Down
0	0	-45.6	0		0	-.513
100	2.8	45.3	10.8	45.3	.121	.496
200	10.0	45.0	21.3	45.0	.234	.495
300	21.5	44.7	31.0	44.7	.342	.492
400	34.0	44.3	40.3	44.3	.446	.488
500	44.5	44.0	48.5	44.0	.530	.484
600	52.5	43.8	55.0	43.8	.600	.482
700	58.7	43.4	58.7	43.4	.649	.478
800	63.6	43.0	63.0	43.0	.699	.472
900	67.1	42.7	66.0	42.7	.726	.470
1000	69.7	41.0	68.8	41.0	.757	.452
1100	71.0	38.4	70.00	38.4	.770	.423
1200	40.0	35.8	40.0	35.8	.440	.395
1300	13.5	35.8	13.5	35.8	.132	-.395
1350	-37.0	-37.0	-37.5	-37.0	-.407	-.407

TABLE II (Cont.)

Second Run on Specimen No.2.

Temp.	Uncorrected Scale		Corrected Scale		% Expansion	
	Up	Down	Up	Down	Up	Down
0	-45.3	-48.5	-45.3	-48.5	0	
100	40.0	48.2	-36.0	48.2	+.107	.033
200	33.0	48.0	-27.6	48.0	.197	.030
300	25.6	47.9	20.0	47.9	.283	.027
400	18.3	47.2	13.0	47.2	.357	.023
500	11.3	46.8	7.5	46.8	.421	-.017
600	-5.0	45.7	-3.0	45.7	.471	-.011
700	+1.0	44.5	+1.2	44.5	.515	.000
800	5.3	43.0	5.0	43.0	.562	+.011
900	9.1	41.0	8.0	41.0	.592	.030
1000	12.0	39.6	11.0	39.6	.622	.051
1100	14.0	38.1	12.6	38.1	.642	.067
1182	+14.5	38.0	13.5	38.0		.078
1200	-3.0	38.0	-3.0	38.0	.470	.087
1300	-17.0	-36.2	-17.0	-36.2	.320	.106
1350	-35.0	-35.0	-35.5	-35.0	.117	.117

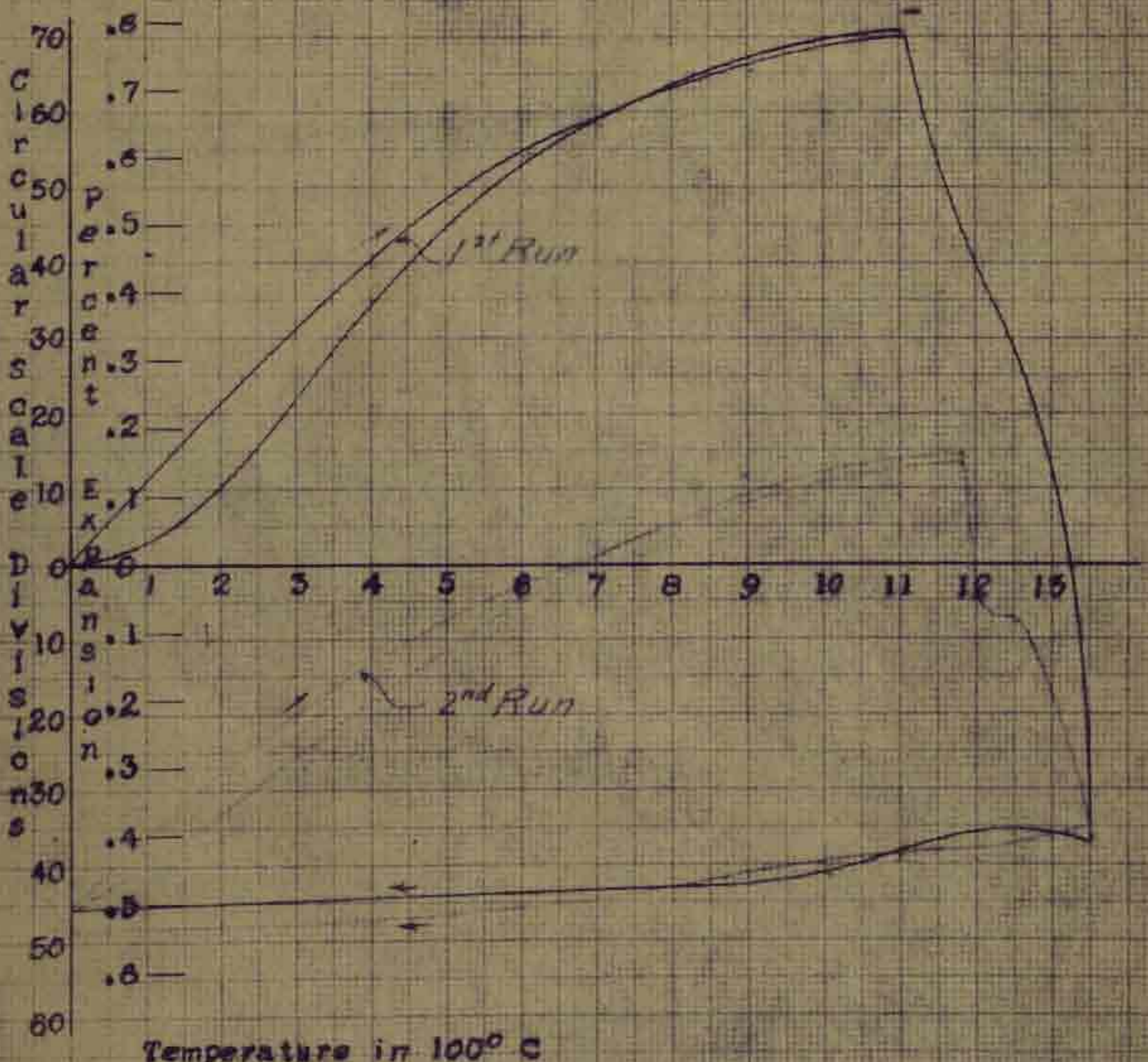
TABLE II (Cont.)

Calculated Data

Temp.	Coef. of Exp. x 10^5			
	1st Run		2nd Run	
	Up	Down	Up	Down
0	0	0	0	0
100	1.21	-4.96	1.07	-.300
200	1.17	-2.98	.98	-.135
300	1.14	-1.64	.94	-.076
400	1.12	-1.21	.89	-.041
500	1.06	- .97	.84	-.022
600	1.00	-.80	.79	.000
700	.93	-.68	.74	+.016
800	.87	-.59	.70	+.037
900	.807	-.52	.66	+.056
1000	.757	-.45	.622	+.067
1100	.700	-.384	.583	+.071
1200	.367	-.329	.391	+.0725
1300	.102	-.304	.246	+.0812
1350	-.301	-.301	.087	+.0870

Graph No. 7

Expansion Curve in Circular Scale Divisions
Of Speciman No. 2



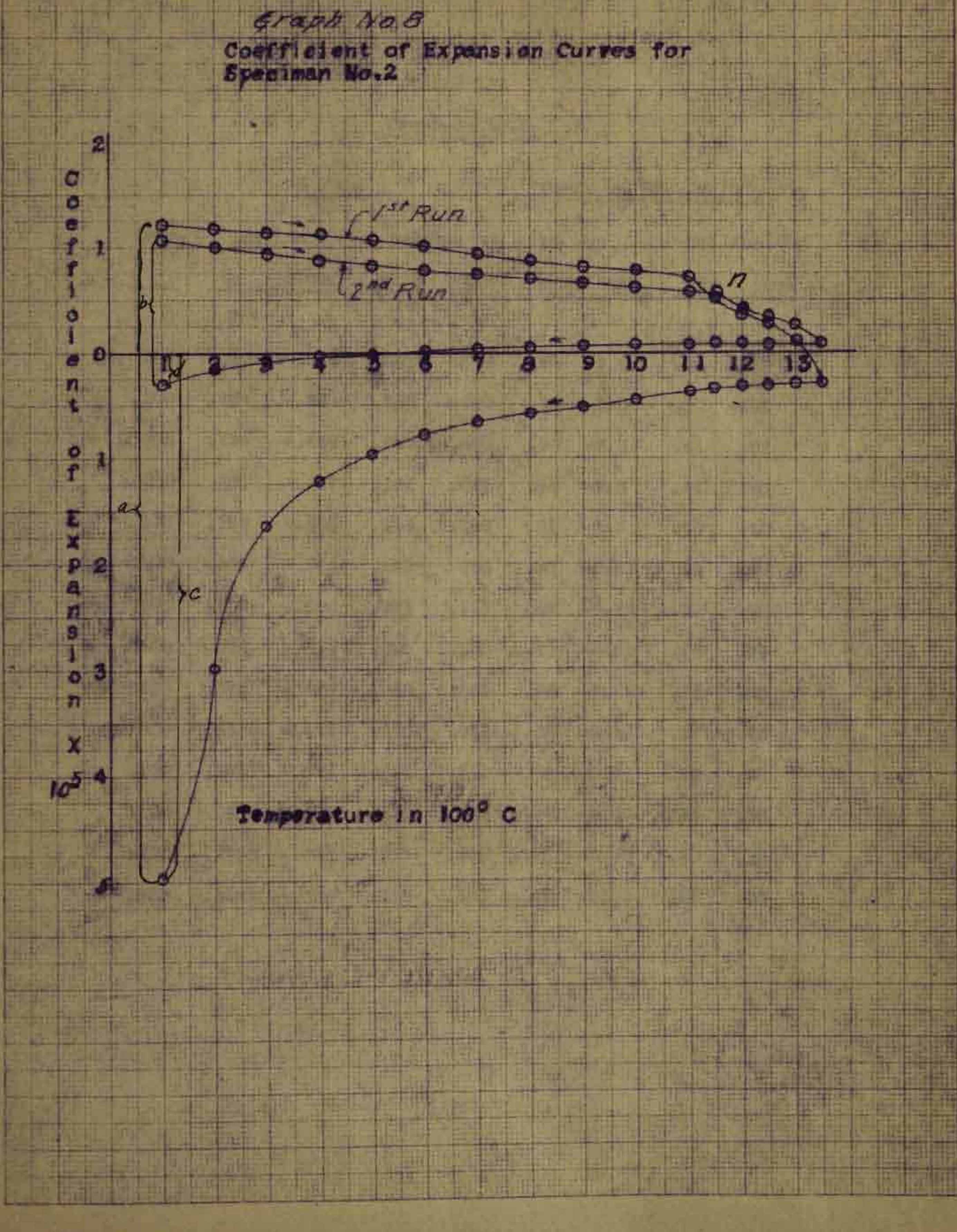
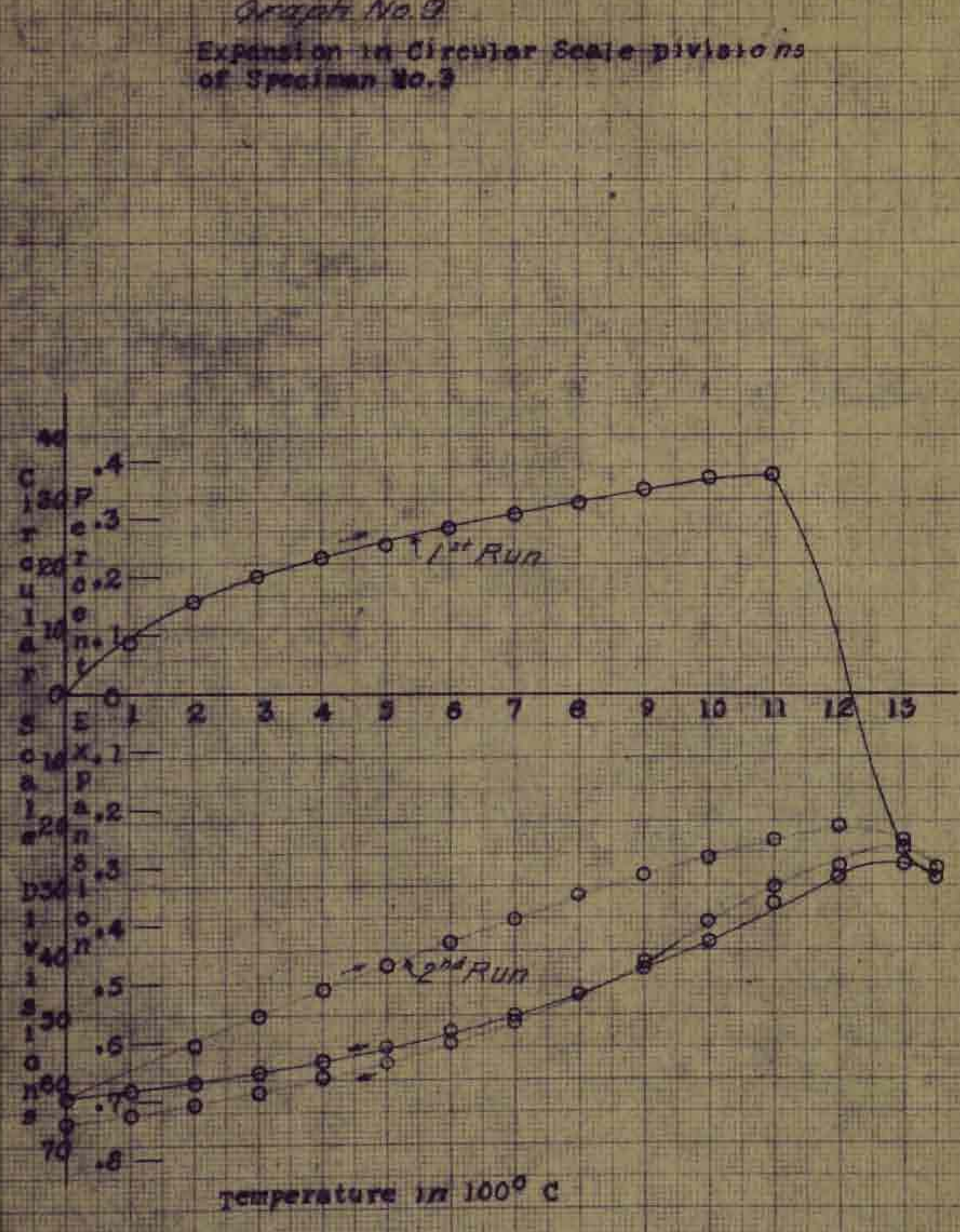

Graph No. 8
Coefficient of Expansion Curves for
Speciman No.2
1st Run
2nd Run
n
a
b
c
d
Coefficient of Expansion X 10^5
2
1
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
12
13
Temperature in 100° C

TABLE III

Specimen No.3

Temp.	% Exp. 1st Run Up	% Exp. 1st Run Down	% Exp. 2nd Run Up	% Exp. 2nd Run Down	Coef. of Exp. x 10^5 1st Run Up	Coef. of Exp. x 10^5 1st Run Down	Coef. of Exp. x 10^5 2nd Run Up	Coef. of Exp. x 10^5 2nd Run Down
0	0							
100	.0933	.676	.043	-.029	.93	-6.8	.43	-.29
200	.154	-.661	.083	-.014	.77	-3.3	.41	-.07
300	.198	-.649	.123	+.003	.66	-2.2	.41	.01
400	.231	-.627	.163	.023	.56	-1.6	.41	.06
500	.259	-.606	.198	.048	.52	-1.3	.40	.10
600	.284	-.583	.235	.093	.47	-0.97	.39	.15
700	.306	-.550	.271	.123	.44	-0.79	.39	.18
800	.326	-.517	.305	.150	.41	-0.65	.38	.19
900	.345	-.473	.338	.203	.38	-0.52	.37	.22
1000	.352	-.429	.366	.263	.35	-0.43	.37	.26
1100	.368	-.374	.393	.320	.33	-0.34	.36	.29
1200	+.0878	-.319	.411	.363	+.073	-0.27	.34	.30
1300	-.2700	-.295	.393	.378	-.210	-0.23	.30	.29
1350	-.3140	-.314	.353	.353	-.23	-0.23	.26	.26



Graph No. 9
Expansion in Circular Scale Divisions
of Specimen No.3
Circular Scale Divisions
Per cent Expansion
1st Run
2nd Run
Temperature in 100° C

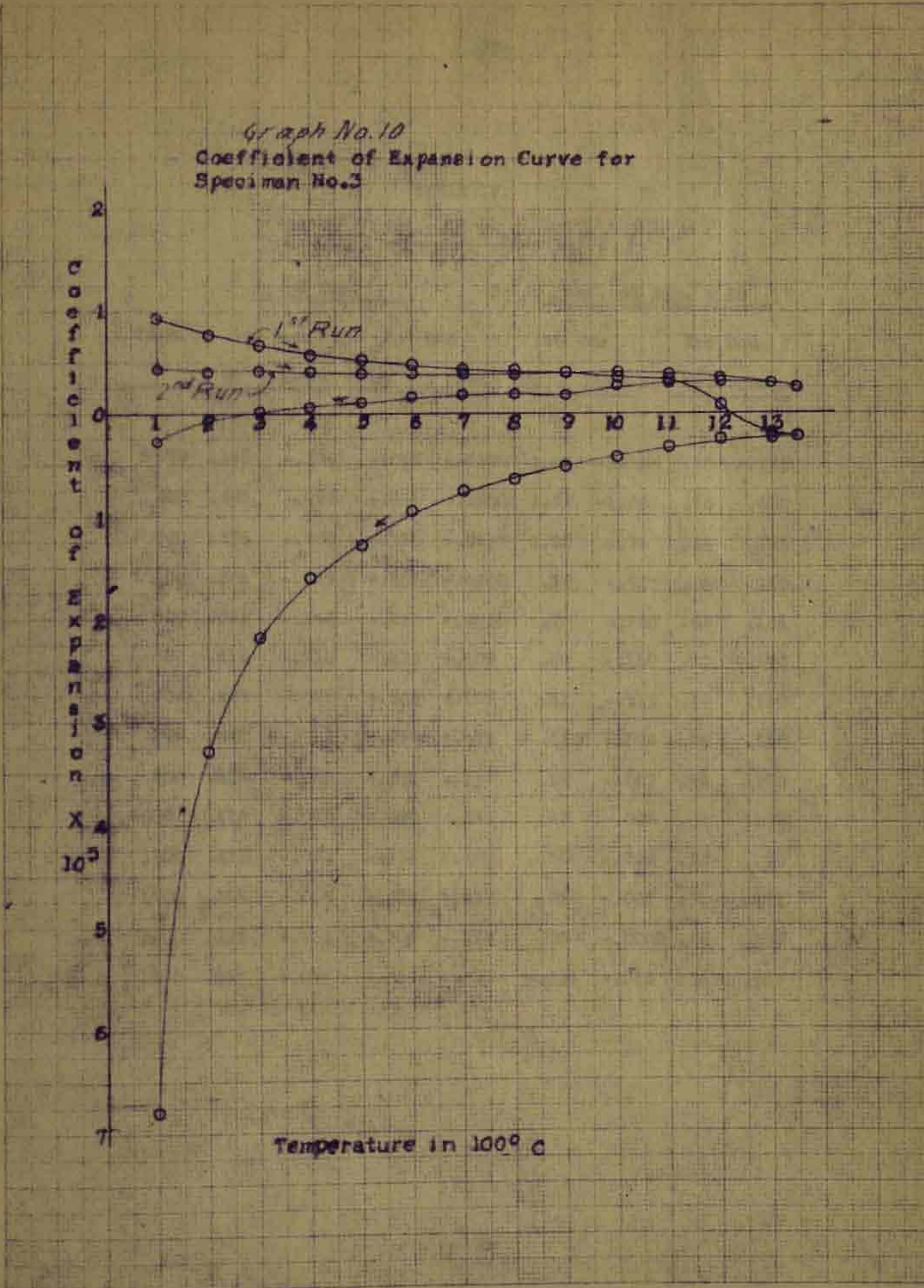
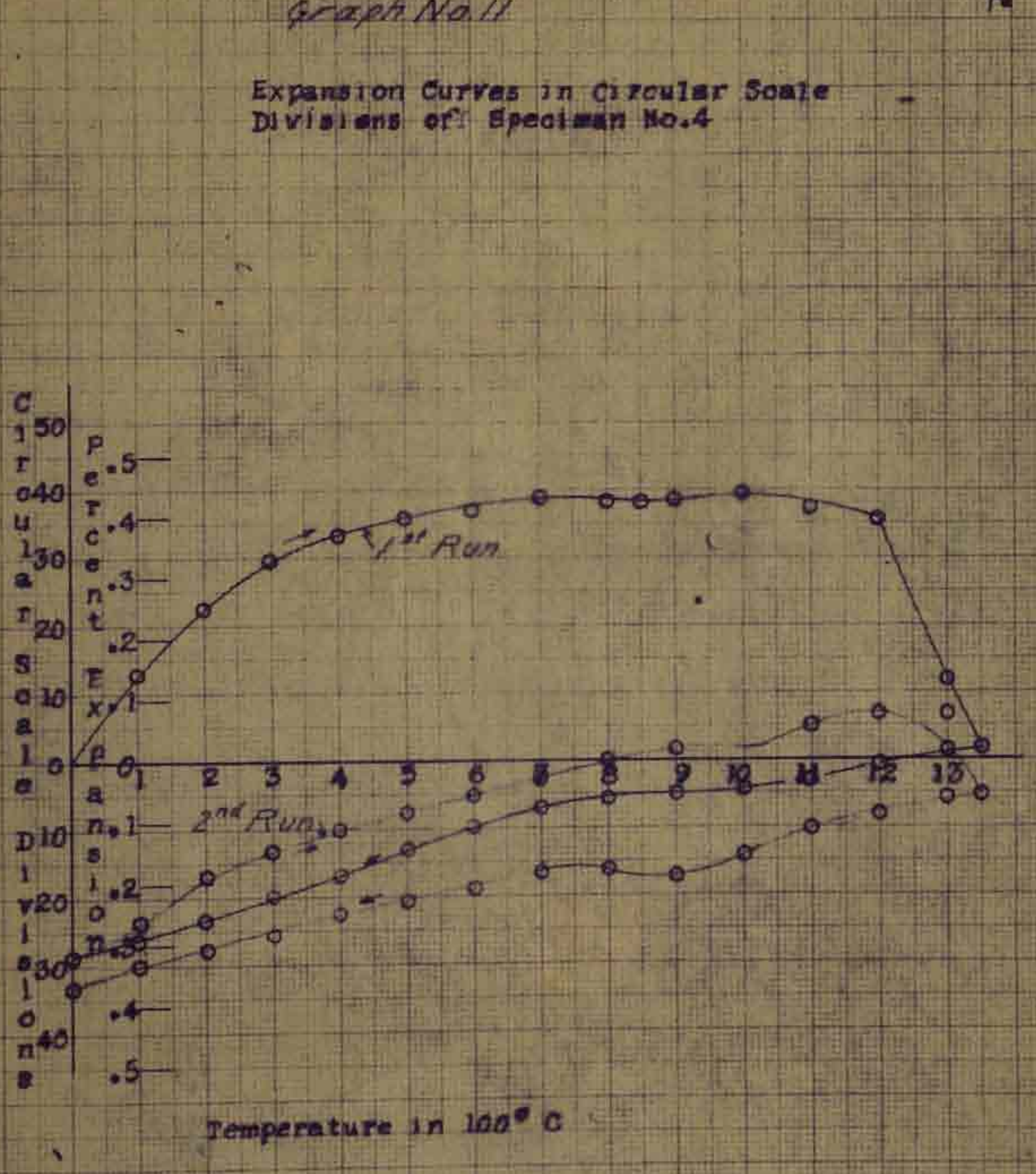

Graph No.10
Coefficient of Expansion Curve for
Specimen No.3
1st Run
2nd Run
Coefficient of Expansion X 10^5
2
1
0
1
2
3
4
5
6
7
1 2 3 4 5 6 7 8 9 10 11 12 13
Temperature in 100° C

TABLE IV.

Specimen No.4

Temp.	% Exp. 1st Run Up	% Exp. 1st Run Down	% Exp. 2nd Run Up	% Exp. 2nd Run Down	Coef. of Exp. x 10^5 1st Run Up	Coef. of Exp. x 10^5 1st Run Down	Coef. of Exp. x 10^5 2nd Run Up	Coef. of Exp. x 10^5 2nd Run Down
100	.165	-.286	+.048	-.0132	1.65	-2.86	.48	-.132
200	.264	-.255	+.115	+.0000	1.32	-1.28	.58	.000
300	.324	-.222	+.154	+.0417	1.08	-.74	.51	.139
400	.368	-.187	+.187	+.0600	.92	-.47	.47	.150
500	.395	-.146	+.212	+.0830	.79	-.290	.42	.165
600	.416	-.110	+.238	+.104	.69	-.180	.40	.170
700	.427	-.078	+.263	+.125	.61	-.111	.38	.180
800	.427	-.061	+.288	+.125	.53	-.076	.36	.155
900	.423	-.055	+.306	+.117	.47	-.062	.34	.130
1000	.428	-.048	+.306	+.145	.43	-.048	.31	.145
1100	.419	-.033	+.336	+.187	.38	-.030	.30+	.170
1200	.395	-.008	+.358	+.217	.33	-.007	.30-	.171
1300	.132	+.001	+.306	+.228	.10	+.0008	.24	.175
1350	.017	+.017	+.236	+.236	+.013	+.013	.187	.187


Graph No. 11
Expansion Curves in Circular Scale Divisions of Specimen No.4
Circular Scale Divisions
Percent Expansion
1st Run
2nd Run
Temperature in 100° C

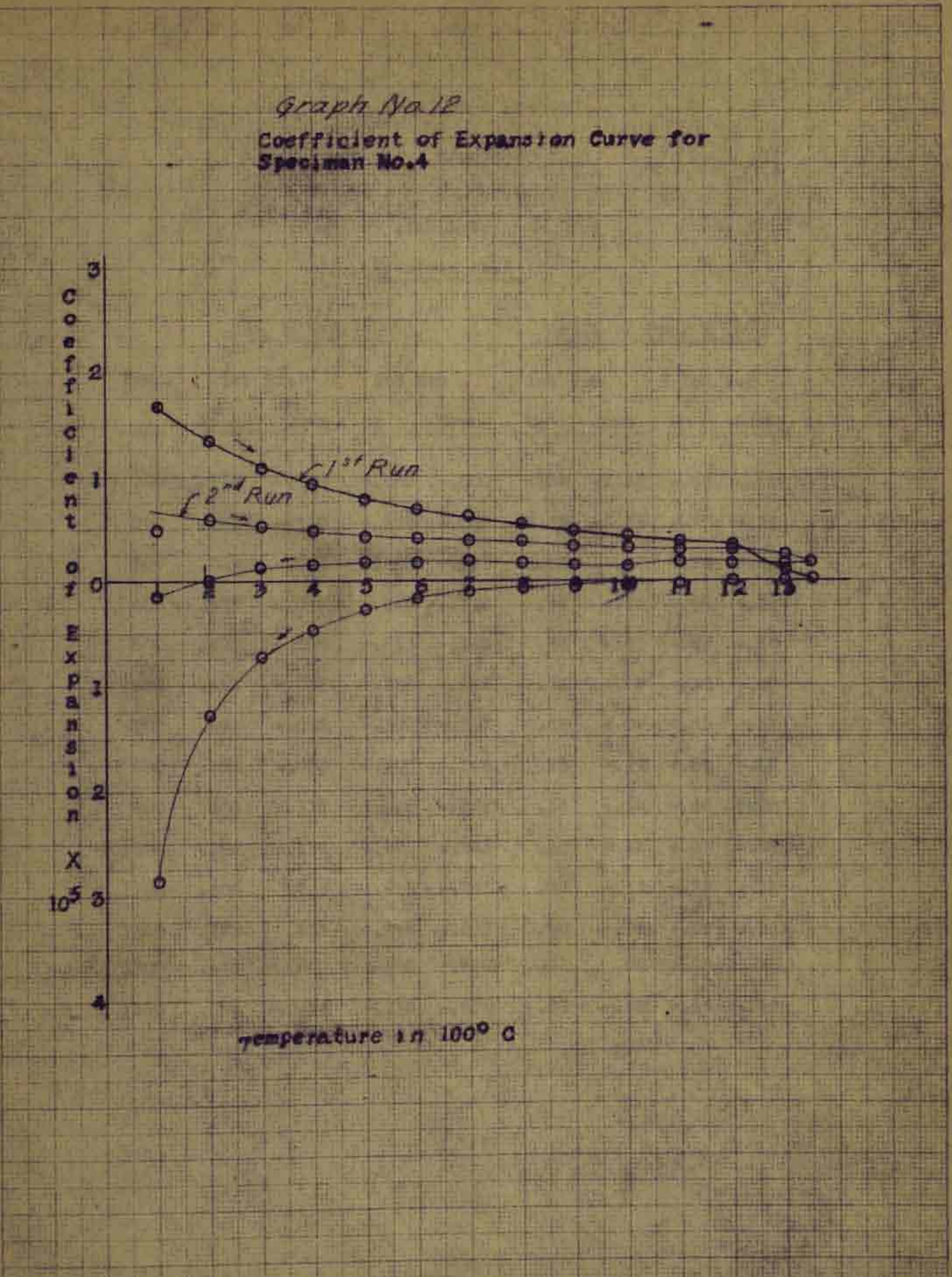

Graph No 12
Coefficient of Expansion Curve for
Speciman No.4
1st Run
2nd Run
Coefficient of Expansion X 10^5
3
2
1
0
1
2
3
4
2
3
4
5
6
7
8
9
10
11
12
13
Temperature in 100° C

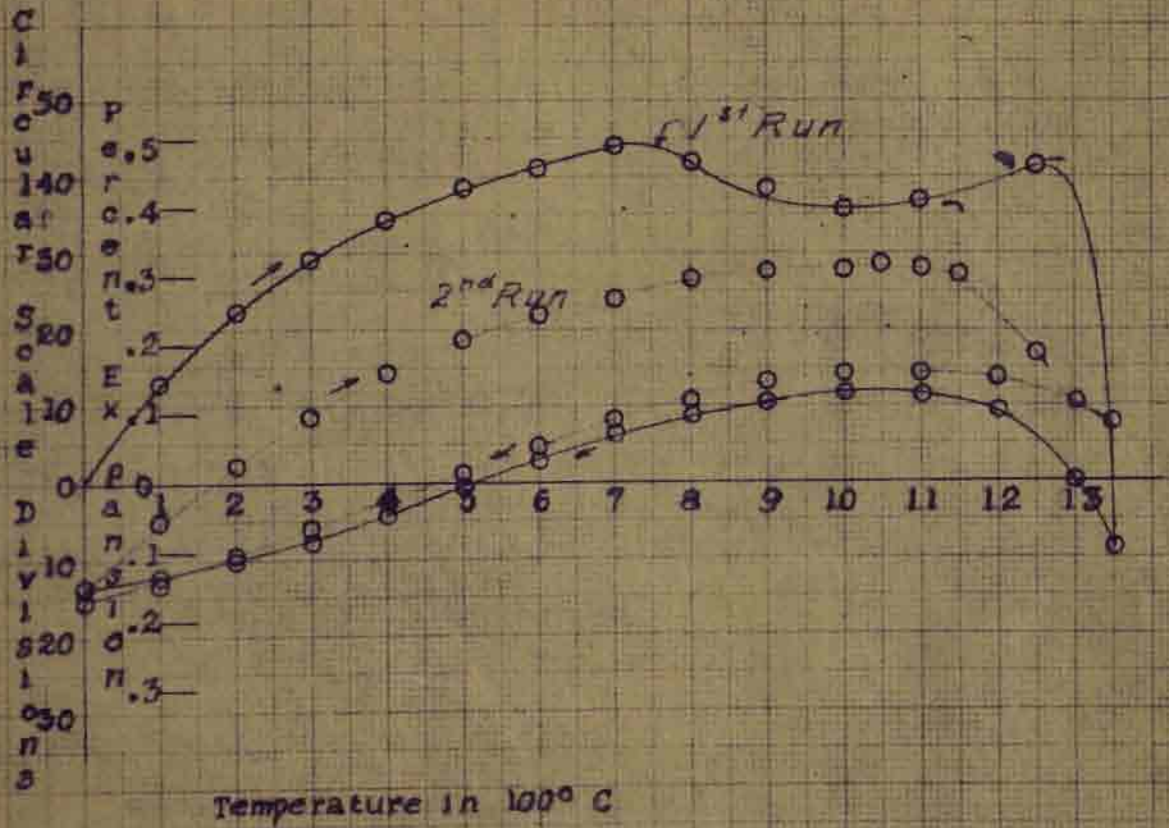
TABLE V.

Specimen No.5

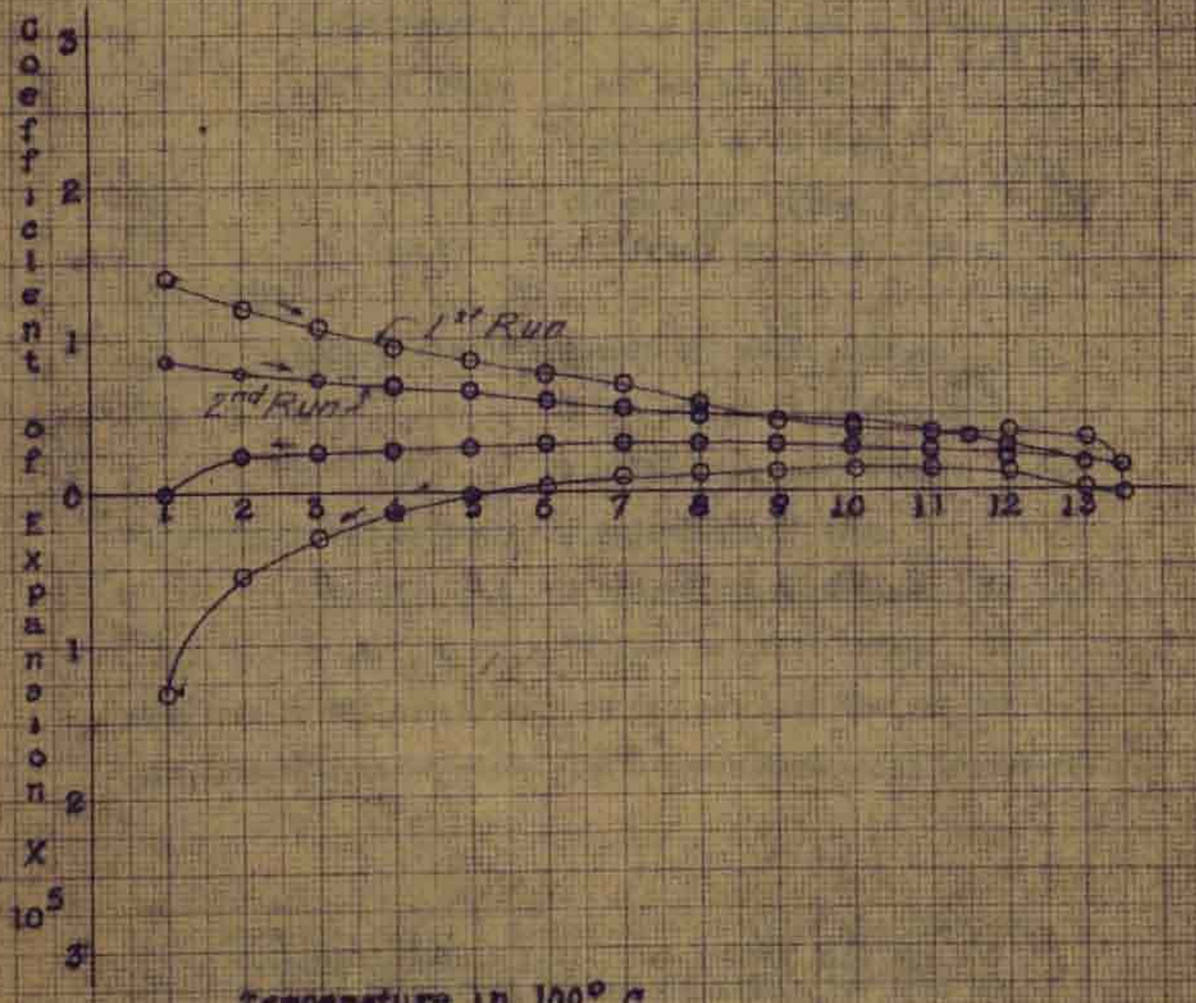
Temp.	% Exp. 1st Run Up	% Exp. 1st Run Down	% Exp. 2nd Run Up	% Exp. 2nd Run Down	Coef. of Exp. x 10^5 1st Run Up	Coef. of Exp. x 10^5 1st Run Down	Coef. of Exp. x 10^5 2nd Run Up	Coef. of Exp. x 10^5 2nd Run Down
100	.138	-.132	+.085	-.000	1.38	-1.32	+.85	-.000
200	.237	-.110	+.158	+.045	1.18	- .55	+.79	+.22
300	.317	-.081	+.223	+.078	1.06	-.27	+.74	+.26
400	.376	-.048	+.278	+.116	.94	-.12	+.69	+.29
500	.421	-.005	+.323	+.149	.84	-.01	+.65	+.30
600	.456	+.033	+.356	+.183	.76	+.05	+.59	+.30
700	.483	+.065	+.383	+.217	.69	+.09	+.55	+.31
800	.461	+.093	+.400	+.248	.58	+.12	+.50	+.31
900	.406	+.115	+.416	+.268	.45	+.13	+.46	+.30
1000	.396	+.130	+.420	+.281	.40	+.13	+.42	+.28
1100	.403	.128	+.416 +.409	+.283	.37	+.12	+.38 .35	+.26
1200	.435	.101	+.358	+.273	.36	+.08	+.30	+.23
1300	.418	.000	+.240	+.240	.32	.00	+.18	+.18
1350	.094	-.094	+.210	+.210	-.03	-.03	+.16	+.16

Graph No.13

Expansion Curves in Circular Scale Divisions of Specimen No.5



Graph No. 14
Coefficient of Expansion Curve for Specimen No.5



DISCUSSION OF RESULTS.

Beinlich ran only two of the brands of brick that were used in this thesis: the Empire and the King. A summary of the data collected by Mr.Beinlich is as follows:[1]

Empire:

Federal Test:	.6% loss at 70 dips on 5 brick.
A.S.T.M. Test:	1 end off at 30 dips,
	1 end off at 42 dips,
	.5% on other three.

King:

Federal Test:	2 ends off at 58 dips,
	1 end off at 67 dips,
	1.0% loss on other three.
A.S.T.M. Test:	1 end off at 41 dips,
	1 end off at 48 dips,
	5% loss on other three.

The loss on all specimens that did not lose the end was in the form of rounded edges with a crack developing transversely,

[1]Beinlich, J.J., A Comparative Study of the Amer.Soc. Testing Materials Spall Test (Water Dip) and the Federal Spall Test (Water Dip with a Pre-heat to 850°C.).

indicating that the end would soon come off, giving total loss of 20% or more.

Data on the other three brands of brick used in this thesis was not available.

Particular note should be taken of point "A" on graphs 8 and 14, and also of the end points of the curves on both graphs. Point "A" is the critical temperature point where the brick specimen began the sharp drop in expansion. This change in the coefficient of expansion is probably due to the bond in the brick becoming softened enough to allow the grog particles to draw closer together. In the Laclede King, there is very little drop at this point as compared with that of the Empire, indicating that the bond had not become fluid; however there was some drop.

Considering the gap between the end points of the expansion curves, the Empire has a much larger gap, indicating that the bond continued to contract.

Just what happens when the bond contracts? In the case of the Empire, where the gap is large and the drop considerable, the bond became fluid enough at the high temperature to flow slightly.

Fig.11 shows what happens when spalling occurs.

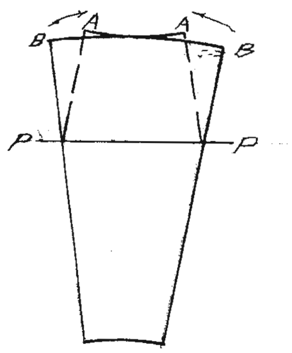


Fig. 11

As has been previously stated (page) the brick upon being heated at one end tends to take the shape of the fan of Fig.11 at points B-B when there is a constant coefficient of thermal expansion. Now then, at the point "A" on the graphs, there was a distinct tendency for the brick end (hot) to contract and form the shape of brick shown at A-A of Fig. 11. This would cause a decided tensile stress in the brick above the plane P-P, which results in the cracking of the brick with the cracks developing perpendicular to the surface. Or, if the bond becomes fluid enough to change its shape and establish an equilibrium of forces at the high temperature allowing the brick to keep the shape at B-B, the stress is relieved; but, if the bond does not establish this equilibrium, there are large direct stresses set up.

It is a commonly known fact that a glass shatters upon cooling and disintegrates, especially if the glass is under a stress or strain. In the brick where the glass has moved to an equilibrium the shattering is not as great as in the one where the equilibrium has not been established.

The fact that the glass has established the equilibrium is indicated by the relative distance between the ends on the first and second runs as given on the coefficient of expansion curves. Because the bond has established the equilibrium, the thermal expansion will upon the second treatment be nearer that of the first run than it is when the bond has not established the equilibrium.

The plane P-P is very significant in this discussion. This plane represents the plane along which the point "A" on the graphs would be drawn. That is, it is the plane where the effect of the shifting of the bond is not felt; nearer the hot end the bond has shifted, and nearer the cool end, the bond is unchanged. It is along this plane that the hot end of the brick tends to rotate when subjected to the stresses here considered. It is here that final great stress is located after chilling the brick due to the contraction to the new length of the brick as given at the final points on Graphs 7 and 13. May it be that this is the plane along which the brick breaks, as was the condition in most of the cases considered by Beinlich? Why do some brick break off nearer the end than others? Take particular note of the point "A" of all of the specimens with relation to the temperature. They are all different. There exists a temperature gradient through the brick along which this critical temperature is located. That plane is where the brick will break. Beinlich found that the crack developed in approximately the same place for each brand of brick, varying with each brand.

Another thing that may be noted: The crack occurred near the waterline of the dip. The brick end that was dipped in the water was subjected to a greater chill than the portion above the water, hence along this line the stress would be greater. However, there was a difference in the position of the crack which would indicate that the equilibrium plane is an important factor. Actual spalling of regractories in service is more commonly of the type where the end breaks than of the type where the brick chips. This is further evidence that the equilibrium plane is an important factor.

In what manner these factors enter into an equation of spalling is possibly so variable that it is of no value; however, consideration of the coefficient of expansion curves of 2 runs on a brick should give some relative indication of the spalling life of the refractory.

Mr.Norton takes into consideration the length of the exposed surface of the specimen. The total contraction in a brick surface due to the bond contraction is proportional to the length of the surface exposed. Consequently the forces acting at the outermost side surface of the refractory piece would be greater in a broad specimen than in a narrow specimen. This would employ the length of the exposed surface as a factor of spalling.

Beinlich found that the brick stood up better under the Federal Spall Test than under the A.S.T.M. Test. This is due to the fact that the bond had a chance to establish equilibrium upon slow cooling, thus relieving the stress. Upon continuing the test after the reheat, this stress that causes the failure did not appear.

COST OF TEST OPERATION.

The cost of construction of the furnace and equipment is practically negligible. The gas used per run amounted to approximately $2.00, making a total of $4.00 per test.

SUGGESTIONS FOR FURTHER STUDY IN SPALLING.

In the above considerations, it was assumed that the bond had become fairly fluid, using the expansion curves as evidence. To just what degree this has taken place was not known. Such a condition could well be studied under a petrographic microscope. It was intended that such a study be included in this report, but time did not permit.

Another consideration, would be to make petrographic slides of a brick subjected to spalling all the way from the heated end to about 2" above the waterline. This might throw some light upon the degree to which the bond has been effected with relation to the temperature gradient. It would also give light upon the position of the plane along which the crack occurs.

This latter effect might be studied with the thermal expansion curves by heating the specimen in series to various temperatures, and cooling up to 1350°C., and studying these under the microscope.

CONCLUSIONS.

The conclusions drawn from this thesis are:

1. The spalling action in any case is due to tensile stresses, both in the end cracking off a brick, and in the chipping of the brick.

2. The point "A" on the coefficient of expansion curves determines the plane along which the brick will crack.

3. The difference in the end points of the coefficient of thermal expansion curves indicates whether or not the brick will chip or crack. If the gap is large and the drop at "A" considerable, the brick will chip.

4. The spalling tendency may be expressed by the formula:

$$S = \frac{a}{b} + \frac{d}{c} + n$$

where,

S = the tendency to spall

$\frac{a}{b}$ = the ratio of the closure gaps of the two runs in terms of coefficient of thermal expansion,

$\frac{d}{c}$ = the ratio of the contraction interceipts of the two runs in terms of the coefficient of thermal expansion,

n = the ratio of the contraction drops in terms of the thermal expansion of the two runs.

APPLICATION TO INDUSTRY.

The spall test that has been devised and in use at present by the A.S.T.M., embodies a rather high initial cost in the furnace, and considerable expense in operation, both in time and fuel. This furnace for thermal expansion is inexpensive in initial cost and very reasonable to operate. If the spalling action can be found with a much smaller expense than is done, it seems that such a small furnace as we propose for thermal expansion could be had by any manufacturer of refractories so that they could run their own spalling tests.

If the properties that determine the spalling can be studied effectively with the thermal expansion data, they may be corrected and thus obtain a better brick from the spalling standpoint. The microscopic study should also enable the manufacturer to better his product from all standpoints.

BIBLIOGRAPHY.

1. Beinlich, J.J., A Comparative Study of the Federal Specifications Spall Test and the A.S.T.M. Spall Test: Thesis for B.S. degree in Ceramics at Missouri School of Mines, 1933.

2. Booze, M.C., A Study of the Spalling Test for Fire-clay brick: Proc.Amer.Soc. Testing Materials, Vol.26, 1, pp.277-280, 1926.

3. Booze, M.C., and Phelps, S.M., A Study of the Factors Involved in the Spalling of Fireclay Refractories, with some notes on the Load and Reheating Tests and the Effect of Grind on Shrinkage: Jour.Amer.Cer.Soc., Vol.8, 6, pp.361-382, 1925.

4. Geller, R.F., The Significance of Elasticity and Thermal Expansion of Fireclays with Reference to the Spalling of the Fired Product: Amer.Refractories Inst.,Tech.Paper 4, 1927.

5. Greene, A.T., and Dale, A.J., The Spalling of Refractory Material: Trans.Eng.Cer.Soc., Vol.25, pp.428-470, 1925-1926.

6. Norton, F.H., The Mechanism of Spalling: Jour.Amer. Cer.Soc., Vol.9, 7, pp.446-461, 1926.

7. Refractories (Textbook): pp.339-368, McGraw-Hill Book Co., 1931.

8. Theory of Spalling: Jour.Amer.Cer.Soc., Vol.16, 10, 1933.

9. Phelps, S.M., A Non-technical Description of Spalling Action: Amer.Refractories Inst., Bull.24, 1928.

10. A Study of Tests for Refractories with Special Reference to Spalling Tests: Amer.Refractories Inst., Tech.Paper 1, 1926.

11. Preston, F.W., Discussion of Norton's Theory: Jour.Amer.Cer.Soc., Vol.16, 3, 1933.

12. The Spalling of Bricks: Jour.Amer.Cer. Soc., Vol.9, 10, pp.654-658, 1926.